

# Muon astronomy with LVD detector

## LVD Collaboration

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## Abstract

We analysed the arrival directions of single muons detected by the first LVD tower from November, 1994 till January, 1998. The moon shadowing effect has been observed. To search for point sources of high energy photons we have analysed muons crossing the rock thickness greater than 3, 5 and 7 km w.e., which corresponds to the mean muon energies 1.6, 3.9 and 8.4 TeV at the surface, respectively. Upper limits on steady muon fluxes for selected astrophysical sources for different muon energies are presented.

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# 1 Introduction:

During recent years major discoveries have been made in very high energy (VHE)  $\gamma$ -ray astronomy. Ground-based experiments operating at TeV energies using atmospheric Cherenkov technique have unambiguously detected  $\gamma$ -rays from a handful of sources at VHE (for recent review see Ong, 1998). Six sources (Crab Nebula, Mrk501, Mrk421, Vela, SN1006 and PSR B1706-44) were observed with significance levels in excess of 6 standard deviations above background. Their spectra have been measured up to maximum energies 10-50 TeV.  $\gamma$ -rays from these sources can initiate muons with probability of order 1%. Muons originate from decay of pions, kaons and charmed particles produced by shower photons and from muon pair production by photons. The production of high-energy muons in gamma-induced showers in the atmosphere and possible detection of muons underground were discussed by Kudryavtsev and Ryazhskaya (1985), Stanev et al. (1985), Stanev (1986), Berezhinsky et al. (1988), Halzen et al. (1997). Since 1985, a number of experiments has looked for a muon excess from known sources and so far the old results of NUSEX (Battistoni et al., 1985) and SOUDAN (Marshak et al., 1985) collaborations which detected muon excess from Cyg X-3 have not been confirmed by other experiments (Ahlen et al., 1993, Giglietto et al., 1997, Poirier et al., 1997). A new interest for muon astronomy arises from the recent success of ground-based  $\gamma$ -ray astronomy.

Single muons observed by LVD detector have been used to search for a possible flux from  $\gamma$ -ray sources discovered by ground-based experiments in the northern hemisphere as well as from some other known sources. Here we present the results of such analysis.

# 2 Detector and Data Analysis:

The data used for the analysis were collected with the 1st LVD tower during 22789 hours of live time. The 1st LVD tower contains 38 identical modules and has dimensions 13m  $\times$  6.3m  $\times$  12m. Each module consists of 8 scintillation counters and 4 layers of limited streamer tubes (tracking detector) attached to the bottom and to one vertical side of the metallic supporting structure. Geometric acceptance for isotropic flux is about 1700 m<sup>2</sup> sr. A detailed description of the detector was given in Aglietta et al. (1992). The depth of LVD site (42°27' N and 13°34' E) averaged over the muon flux is about 3650 hg/cm<sup>2</sup> which corresponds to the median energy of vertical muons at sea level of about 2.2 TeV. LVD detects muons crossing from 3000 hg/cm<sup>2</sup> to more than 12000 hg/cm<sup>2</sup> of rock (which corresponds to the median muon energies at sea level from 1.6 TeV to 40 TeV for conventional atmospheric muons) at zenith angles from 0° to 90° (on the average, larger depths correspond to higher zenith angles). This allows us to analyse muons in different energy ranges. Three muon samples have been chosen in our study: 1) muons crossing all column densities of rock (corresponding energy threshold defined as the median surface energy of conventional vertical muons which cross the minimal rock thickness of 3 km w.e.,  $E_{\mu}^{thr}$ , is equal to 1.6 TeV), 2) muons crossing rock thickness greater than 5 km w.e. ( $E_{\mu}^{thr}$ =3.9 TeV) and 3) muons crossing rock thickness greater than 7 km w.e. ( $E_{\mu}^{thr}$ =8.4 TeV).

Muon celestial coordinates have been stored in two dimensional map with a cell size of 1° in right ascension (R.A.) and 0.01 in  $\sin \delta$  (where  $\delta$  is declination).

### 3 Results and Discussion:

We used the shadowing of cosmic rays by the Moon to confirm the pointing accuracy of the LVD detector. The data used in the search for the shadow of the Moon included  $1.85 \cdot 10^6$  muons. For every muon arrival time, R.A. and  $\delta$  of the geocentric apparent position of the center of the Moon has been computed taking into account the corrections for parallax. The angle between muon direction and the position of the center of the Moon has been evaluated. We simulated the background events from the experimental zenith-azimuthal distribution of muons and the mean time between two consecutive muons observed by LVD run by run. Then the angle between background event and Moon position has been calculated. Figure 1 shows the angular density  $dN/d\Omega$  as a function of the angular distance from the center of the Moon. The observed deficit has a significance of 2.62 standard deviations (s.d.). This study confirms that the track reconstruction and pointing accuracy have no serious systematic errors.

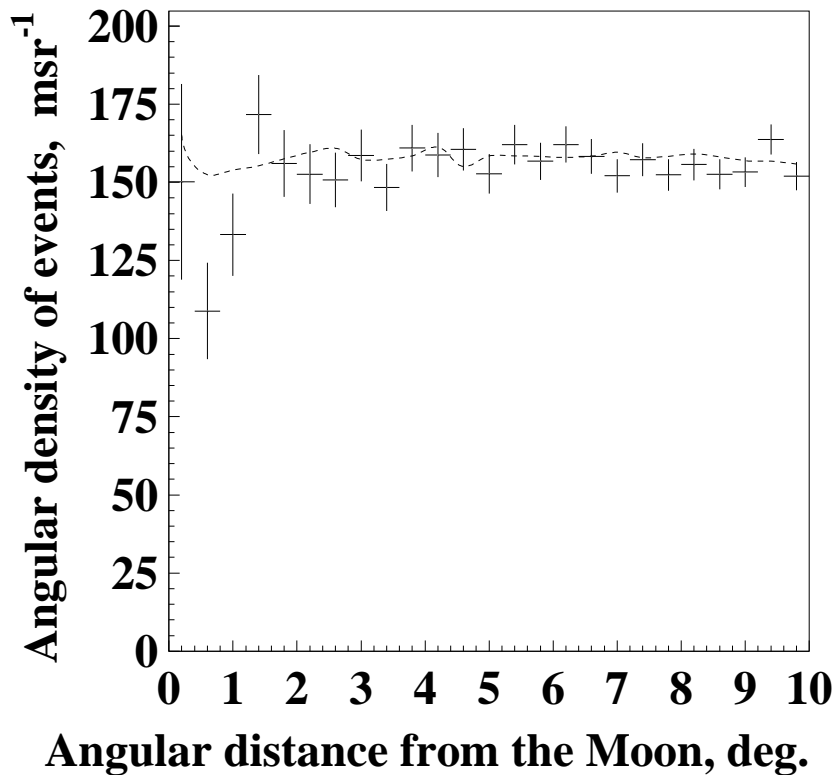


Figure 1: The angular density  $dN/d\Omega$  as a function of the angular distance from the Moon; the distribution for the simulated background events is shown by dashed line.

The distribution of the data versus declination (after summing over R.A.) for three selected ranges of depth is presented in Figures 2a, 2b, 2c together with calculated background of atmospheric muons. The difference in the distributions for three depth ranges reflects different mountain structure for these regions at LVD site. Figure 2d shows the distribution of the muon flux versus R.A. (summed over declination). The calculated background fits data for three analysed depth ranges rather well.

To test the presence of a significant muon excess above the background from any angular cell in the sky we used cells of equal solid angles with a width of  $3^\circ$  in R.A. and

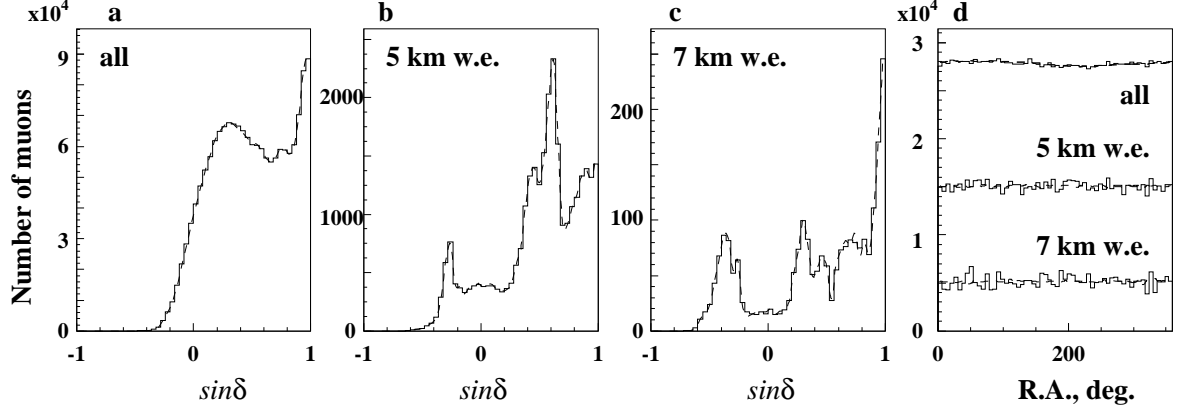


Figure 2: Distribution of muon events vs  $\sin \delta$  (a,b,c) and R.A. (d) for three depth ranges analysed. The histograms are experimental data, dashed curves show simulated backgrounds from atmospheric muons initiated in hadronic showers. The histograms for the second and the third depth ranges in Figure 2d were multiplied by factors of 15 and 66, respectively.

0.04 in  $\sin \delta$  which corresponds approximately to the solid angle of a cone with a half angle of  $1.5^\circ$ . The deviation from the mean was computed using the Gaussian statistics  $\frac{n_{exp} - n_{mc}}{\sqrt{n_{mc}}}$ , where  $n_{exp}$  is a number of muons observed in the experiment and  $n_{mc}$  is the simulated background from atmospheric muons. No cell with an excess of more than 3.5 s.d. has been found for the first depth range. The Gaussian fit gives  $\chi^2/Dof = 0.86$ . For the second range we found two cells with excesses of 3.72 s.d. and 3.84 s.d. and worse Gaussian fit with  $\chi^2/Dof = 1.41$ . We shifted the cells by  $1^\circ$  in R.A. and 0.01 in  $\sin \delta$ , repeated this procedure and did not find any excess more than 3.5 s.d. in the overlapping bins. To have better statistics for the third depth range the cells have been enlarged up to  $10^\circ$  in R.A. and 0.1 in  $\sin \delta$ . Two bins with excesses of 4.19 s.d. and 3.83 s.d. were found but disappeared after the cells were shifted in the same way as for the second depth range. Gaussian fit for this range gives  $\chi^2/Dof = 1.29$ . We conclude that we have not found significant excess of muons over background from any cell on the sky in the selected depth ranges. Figure 3 shows the results of this study.

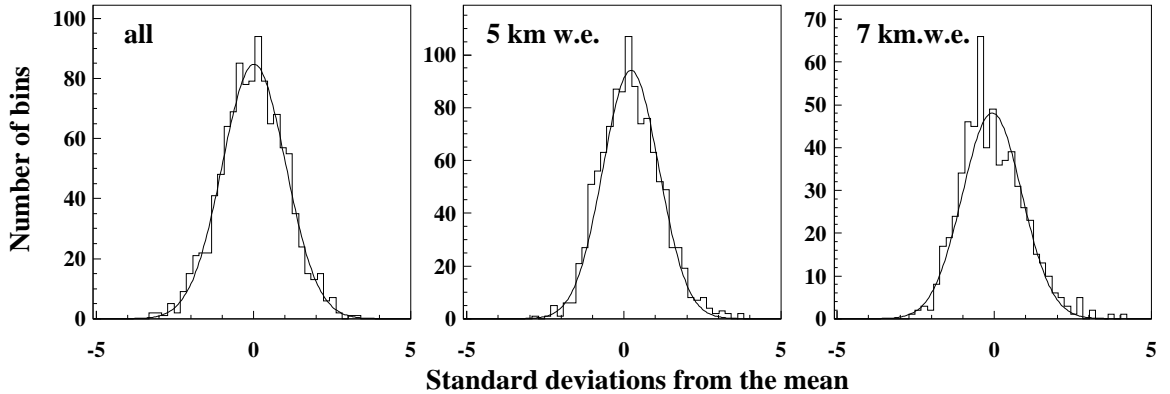


Figure 3: Distribution of deviations from the mean value of muon flux and Gaussian fit.

We have also made a search for a possible flux in narrow cones ( $1.5^\circ$  half angle)

around the position of the sources observed in  $\gamma$ -ray ground-based experiments (visible in the northern hemisphere) and some other sources which have drawn attention of underground experiments during the last decade. Again the data from three depth ranges were considered. To obtain an upper limit (95% C.L.) on the flux from a source we used the following formula:

$$F = \frac{n_\mu}{f \cdot \langle \epsilon \cdot A \rangle \cdot k \cdot T} \quad (1)$$

where  $n_\mu$  is the upper limit on the number of muons calculated according to the procedure given in (Helene, 1983),  $f=0.9$  is correction factor to calculate the muons scattered out of  $1.5^\circ$  half angle cone, this factor is estimated taking into account muon deflection in the rock convolved with the simulated detector response function for single muons,  $\langle \epsilon \cdot A \rangle$  is the weighted average of the product of efficiency of muon detection and reconstruction times the area of the cross-section of the detector perpendicular to the muon track, it depends on source position and the depth range, for Cyg X-3 and the first depth range  $\langle \epsilon \cdot A \rangle = 84 \cdot 10^4 \text{ cm}^2$ ,  $k$  takes into account the time when the source is visible and  $T$  is the exposure time. The results are presented in Table 1.

Table 1: Steady flux limits (95% C.L.) from selected sources.  $N_{all}$ ,  $N_5$  and  $N_7$  show the number of muons observed (simulated) in the corresponding cones for three depth ranges,  $N_7^{cut}$  is the same value after depth cut (see text for details),  $F_{all}$ ,  $F_5$  and  $F_7$  are the flux upper limits (95% C.L.) multiplied by a factor  $10^{13}, \text{ cm}^{-2}\text{s}^{-1}$

Source	$N_{all}$	$N_5$	$N_7$	$N_7^{cut}$	$F_{all}$	$F_5$	$F_7$
Cyg X-3	474(506)	26(32)	1(1.4)	1(0.9)	11.7	3.70	1.17
Her X-1	528(544)	44(34)	1(1.3)	1(0.9)	14.2	7.66	1.28
Crab Nebula	618(620)	19(17)	1(0.6)	1(0.5)	19.5	3.51	1.46
SS433	499(465)	5(8)	0(0.2)	0(0.2)	29.5	2.18	1.29
3C273	429 (405)	5(7)	0(0.4)	0(0.4)	28.3	2.71	1.46
Geminga	653(629)	14(10)	3(1.5)	3(1.4)	25.2	4.37	2.33
Mrk 421	565(528)	36(44)	3(1.6)	1(1.0)	21.5	4.79	1.28
Mrk 501	497(503)	47(38)	6(1.4)	4(1.0)	13.5	7.44	2.44

No statistically significant enhancement (more than 1.5 s.d.) of observed muons above calculated background of atmospheric muons has been found from any source for all-depth range and for slant depths greater than 5 km w.e. For the range of slant depths more than 7 km w.e. 6 muon events against the background of 1.4 events were observed from the angular cell which includes Mrk 501 (this corresponds to the probability of 0.0031). However the excess can be connected with the complicated mountain structure at these depths. To test this hypothesis a special depth cut has been applied both for the observed and simulated events. For every muon we calculated the depths for nearby cells at an angular distance of no more than  $3^\circ$ . As mean angular deviation of muons during their passage through the rock, mainly caused by multiple Coulomb scattering, is about  $0.5^\circ$  (Antonioli et al., 1997), we excluded events if the slant depths in the nearby cells were less than 6.5 km. The values in the column  $N_7^{cut}$  of Table 1 show the results after this cut. As a result of the depth cut we have 4 muon events against 1 background event which corresponds to the probability of 0.019.

During 1997 Markarian 501 had a remarkable flaring activity and was the brightest source in the sky at TeV energies. We used LVD data to look at possible enhancement of observed muons above calculated background during the period of Mrk501 activity from the middle of March till the end of August, 1997. The results are presented in Table 2.

Number of muons	all depths	> 5 km w.e.	> 7 km w.e.	> 7 km w.e. after depth cut
Observed	101	5	1	1
Simulated	95	5.1	0.4	0.3

## 4 Conclusions:

We have confirmed a lack of serious systematic errors both in reconstruction of muon direction and pointing accuracy of the LVD detector by observing the effect of the Moon shadow with a statistical significance of 2.62 s.d. Three depth (muon energy) ranges have been selected to search for point sources of VHE gammas. No statistically significant excess of muons above the simulated background has been found from any angular cell on the sky and for all energy ranges included in the analysis procedure. We have not found either any enhancement of muon flux from the angular cells which include some known astrophysical sources.

## 5 Acknowledgements:

We wish to thank the staff of the Gran Sasso Laboratory for their aid and collaboration. This work is supported by the Italian Institute for Nuclear Physics (INFN) and in part by the Italian Ministry of University and Scientific-Technological Research (MURST), the Russian Ministry of Science and Technologies, the US Department of Energy, the US National Science Foundation, the State of Texas under its TATRP program, and Brown University.

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